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Kinetic characterization of photoionized plasma evolution from FEL pulse interaction with gas jet

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Abstract

The characterization of a photoionized plasma created through the interaction of a short, 50–100 fs, linearly polarized X-ray pulse with an He gas jet is presented by using Monte Carlo (MC) simulations. A kinetic description, which takes into account electron production due to photo-effect, elastic electron scattering on atoms, ionization and excitation of atoms by the secondary electrons, and electron transport across the X-ray beam, is introduced to study relaxation of the electron distribution function (EDF) and evolution of the electron density and mean energy. It is shown that initially an anisotropic monoenergetic EDF forms. Then it relaxes to a monoenergetic isotropic EDF for the case of low-energy X-ray quanta or to a quasi-multi-monoenergetic isotropic EDF for a pulse of high-energy X-ray quanta. This nonequilibrium electron energy distribution remains long after the X-ray pulse terminates and disappears on a ps-time-scale. The electron density distribution in the plane across the X-ray beam is characterized by considerable asymmetry along and across the polarization direction even after the vanishing of the electron energy anisotropy. The results obtained are discussed in the context of future design of experiments on self-Thomson scattering and Thomson scattering of a probe laser beam in a plasma produced by femtosecond FEL pulses.

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1. Introduction

Recent progress in the development of high intensity free electron lasers (FEL) [1,2] opens the door to systematic study of plasmas produced due to the photoionization of gas (gas jet) by using coherent femtosecond X-ray pulses. The typical photon energy, $\hbar\omega$, pulse-duration, τ, spot size, d, and number of photons per shot, N_γ, are: $\hbar\omega \gtrsim 50$ eV, $\tau \sim 50$ fs, $d \sim 20$ μm, and $N_\gamma \sim (1-5)\times 10^{12}$, correspondingly. Planned programs will see photon energy increase to $\hbar\omega \gtrsim 1$ keV [3]. This will facilitate plasma experiments involving self-Thomson scattering or Thomson scattering of a probe laser beam to study the evolution of the electron distribution function (EDF) on the time scales of either the X-ray pulse-duration or much longer scales after the plasma formation [4].

FEL laser produced plasmas are expected to be different from plasmas created by conventional optical pulses because an intense X-ray beam with a photon energy of several tens of eV is sufficient to ionize atom by single photon absorption through the classical nonrelativistic photoelectric effect [5]. Photoelectrons leaving the atoms with energy $\epsilon = \hbar\omega - I$ (I is the ionization potential of the atom) escape predominantly along the direction of polarization of the X-ray pulse, thereby

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creating a plasma with an anisotropic electron energy distribution. Thus, rarefied plasmas for which the electron–electron collisional time is significantly longer than the pulse-duration, will exist in a nonequilibrium state until electron–electron collisions relax the EDF to a Maxwellian. It has already been demonstrated that the VUV radiation from FEL ionizes atoms and clusters through the photoelectric effect [6].

Photoionized plasma with anisotropic EDF can give rise to new electromagnetic effects including anisotropic plasma waves, two-stream and Weibel instabilities, self-generated magnetic field, and electromagnetic emission [7]. Therefore, the study of relaxation of the anisotropic EDF is of great interest as it plays an important role for these effects. As long as the FEL reaches an intensity which corresponds to $N_\gamma \sim d^2/\Sigma \sim 10^{13}$, where Σ is the total cross-section of photoionization, the FEL produced plasma is weakly ionized and its evolution can be considered neglecting both electron–electron and electron–ion Coulomb collisions. This case is a subject of our paper.

In this paper, by using MC simulations we study photoionization of gas by a short, linearly polarized X-ray pulse and relaxation of the weakly ionized plasma created, in the context of gas jet experiments with femtosecond FEL sources in the gas density range of 10^{18}–$10^{19}\,\mathrm{cm}^{-3}$. As an example He gas is considered. The after-pulse evolution of photoionized plasma is determined by the elementary processes such as elastic electron–atom collisions, ionization of atoms, and atom excitations. Relaxation of the EDF and evolution of plasma channel are studied up to times of two orders of magnitude longer than the FEL pulse-duration. We discuss plasma evolution for different EUV wavelength from the low-energy end of EUV radiation ($\hbar\omega = 40$ eV) to the high-energy end of EUV ($\hbar\omega = 300$ eV). The Monte Carlo simulations allow us to observe the evolution of the nonequilibrium EDF for these weakly ionized plasmas in the presence of collisions at relatively high gas densities, a regime not studied before. We consider this an important first step towards understanding the plasma evolution in the case of highly ionized plasma, when $N_\gamma > d^2/\Sigma$ and plasma evolution becomes much more complex once one introduces the collective kinetic phenomena.

The paper is organized as follows. In Section 2 we describe the physical model of photoionized plasma relaxation and corresponding MC model for numeric calculations. Section 3 is devoted to a description of plasma evolution in the case of soft EUV photons ($\hbar\omega = 40$ eV) when their energy slightly exceeds the threshold of the photoelectric effect, $\hbar\omega - I < I$. A similar description is presented in Section 4 but for relaxation of plasma produced by more energetic EUV photons ($\hbar\omega = 100$ eV and $\hbar\omega = 300$ eV) for which $\hbar\omega - I \gg I$. We conclude with a discussion and summary in Section 5.

2. The Monte Carlo model

The linear polarized (along X-axis) coherent X-ray pulse of FEL propagates along Z-axis in He gas. The X-ray pulse has a rectangular shape in time with duration $\tau = 50$ fs and homogeneous intensity in the XY-plane within a circle of diameter $D = 20\,\mu\mathrm{m}$ (homogeneous cylindrical beam). When the X-ray pulse enters the gas it ionizes He atoms if the photon energy, $\hbar\omega$, exceeds the threshold $I = 24.6$ eV. Photoelectrons leave the atoms predominantly in the direction along the X-ray polarization, in accordance with the differential cross-section [5]

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}\cos\theta\,\mathrm{d}\varphi} = \Sigma(\hbar\omega)\frac{3}{4\pi}(\sin\theta\cos\varphi)^2, \tag{1}$$

written for spherical coordinate system with the reference axis along the propagation direction of the X-ray pulse. Eq. (1) describes standard anisotropy $\propto \cos^2\Theta$ of the outgoing photoelectrons, where Θ is the angle between electron velocity and X-ray polarization direction. The photoionization cross-section in He decreases with the photon energy as: $\Sigma = 3$ Mb, for $\hbar\omega = 40$ eV, $\Sigma = 0.34$ Mb, for $\hbar\omega = 100$ eV, and $\Sigma = 0.015$ Mb, for $\hbar\omega = 300$ eV. The photon transport is not modeled and the longitudinal distribution of the electron photoproduction in homogeneous gas medium ($z > 0$) is assumed to be proportional to $\Sigma\exp(-\Sigma z)$. Time points of photoelectron production were randomly sampled with the same probability for $0 \le t \le \tau$. Because of the extremely short time, $\tau = 50$ fs, no electron collisions occur during the pulse-duration.

The behavior of electrons in He gas with atom density $n_\mathrm{a} = 5 \times 10^{18}\,\mathrm{cm}^{-3}$ is calculated by MC direct simulation method with semi-infinite simulation box, $z > 0$. Particle interactions are modeled until the run stops at the desired point of time. We considered three examples: $\hbar\omega = 40, 100, 300$ eV with the total number of primary photoelectrons 10^8, 5×10^7, and 10^7, for simulation times, 55.3 ps, 108 ps, and 244 ps, respectively. Atoms are assumed immovable. The simulation box is divided into cells in the cylindrical coordinate system: partitions in z-direction (10 bins), sectoring (20 bins), and radial partitions (15 bins). The calculation in velocity space is performed by a three-dimensional model. The velocity space is not divided into cells while the code generates the averaged electron velocity component and the averaged squared electron velocity component for each space cell. There are no time steps, although the simulation time is broken into 50 time intervals for analysis purposes. This gives a total number of space-time cells of 150 000. The code samples the elastic and inelastic mean free path and redistributes particles at the time point of electron collision in accordance with their coordinates and current time.

The performed simulations include photoionization of helium atoms, electron elastic collisions with atoms, electron impact ionization of atoms from the ground state, and excitation of the main atomic levels. These processes with corresponding integral cross-sections are illustrated by Fig. 1, where the data from Ref. [8] are used [9]. This model is applied to weakly collisional plasma where Coulomb collisions and plasma self-consistent electric fields can be neglected. This gives the following restriction on the total number of photons in the pulse $N_\gamma \ll d^2/\Sigma$, e.g. for 100 eV photon energy this inequality reads $N_\gamma \ll 10^{13}$. Recombinational processes are not